The Final Report

Title: Specific approach for size-control III-V based quantum/nano LED fabrication for prospective white light source

Principal Investigator:
Huey-liang Hwang, Ph.D., Professor

Nano Technology & MEMS Center and Institute of Electronic Engineering
National Tsing Hua University
101, Sec. 2, Kuang-fu Road
Hsinchu 300, Taiwan
Telephone: +886- 3-571-5131(EXT: 42207)
Facsimile: +886- 3-572-3927
E-mail: hlhwang@ee.nthu.edu.tw

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Huey Liang Hwang

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National Tsing Hua University,No. 101, Sec. 2, Kung-fu Rd,Hsinchu 30013,Taiwan,TW,300 13

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14. ABSTRACT
This research achieved a nano-structure LED to enhance the light extraction efficiency in III-V nitride LED. The Triangular lattice PC LED with diameter/periodicity of 300/500nm were patterned separately using the AAO template, E-beam lithography, and then the ICP etching technique. The PC LED could get low and stable forward voltage as compared to the AAO LED and conventional LED. The optical and electrical properties of the nano-structure LED was demonstrated in this project.

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1-1. Introduction

Wide-gap III-Nitride based white light emission had been proven to yield luminescence efficiency (30-40 Lumen/W) and the III-Nitride devices proved long lifetime (>10khr). III-Nitride semiconductors have attracted much attention especially for the LED. The applications are shown in Figure 1. It is expected that high efficiency III-Nitride based white light emission will be the major lighting source for daily illumination in the coming decades. To further largely improve the luminescence efficiency beyond 100 Lumen/W and to increase thermal stability of the III-Nitride based LED, devices in the nano/quantum structure is the viable way to pursuit.

The efficiency of the conventional wide-gap III-Nitride based white light emission with a multi quantum well (MQW) structure of III-nitride device was typically limited to 30 to 40lm/w due to the low Wall-Plug-Efficiency (WPE) as-depicted in the following ;

WPE = $\eta_{in} * \eta_{ext} * \eta_{el}$

Where WPE is the Wall-Plug-Efficiency, η_{in} is the internal quantum efficiency, η_{ext} is the extraction efficiency, and η_{el} is the electrical efficiency. There are three dominant limiting factors governing WPE in the III-nitride device.

1-2. The WPE issue in the III-Nitride nano-device

For the nano-structure for LED, the WPE will be largely increased. While the dot size is smaller than 50nm and the dot spacing is smaller than 50nm. The dot density will be higher than $10^{11}cm^{-2}$, which will be higher than the conventional dislocation density (10^{7}~$10^{9}cm^{-2}$), and the η_{in} will be higher than 90%.

With nano-structure inside the activation layer, the spontaneous rate will be enhanced by a Factor and the η_{el} will also be increased, due to the Purcell effect with micro-cavity, as indicated in the equation shown below.

Factor=$3\lambda^{3}Q/4\pi2V$

Where λ is the wavelength, Q is the quality factor, and V is the cavity volume. The η_{el} could be increased due to the low serial resistance of nano device as discussed above. The η_{ext} could be largely increased to 70% with the photonic crystal structure [1] or rough cavity structure [2] or the nano-dots embedded in the activation layer.

The Light extraction efficiency enhanced by photonic crystal structure is shown in

Figure 2. The total internal reflection is suppressed by the nano-photonics structure.

1-3. The nano-structure fabrication

We used two methods for the nano-structure fabrication of GaN. The first one was the electrochemical etching method for the AAO structure. The other one was the E-beam pattern structure.

1-3-1. Nano-structure fabrication by AAO method

The facility of the anodic oxidation system is shown in Figure 3. The heater and cooling system could be used to keep constant temperature during the etching. The anodization procedure is shown in Figure 4 in which the second anodization was applied to get the high quality nano-structure. Figure 5 show the experiment results of the AAO layer. Typically, a random distribution of nano holes with different sizes can be observed. The holes size was about 50nm, ant the depth of the holes was about 0.5um. When the anodic voltage was high, the AAO template became uniform, but the nano-holes density was reduced. We use the low anodic voltage process to get the uniform nano-holes.

1-3-2. Nano-structure fabrication by E-beam lithography method

The e-beam lithography system was also used to generate the photonic crystal (PC) LED. The SEM of the 2D PC structure by E-beam lithography method is shown in Figure 6.The diameter of the nano-hole is 300nm, the lattice constant is 500nm, and the etching depth is 100nm. This dimension was designed to increase the light extraction efficiency.

1-4. Optical and electrical properties of the nano-structure LED

The optical properties were compared between AAO, PC and conventional structure LED. The photoluminescence spectrum is shown in Figure 7. The peak wavelength is ~473nm. The AAO and PC LED separately enhanced the emission intensity of about 3.5-fold and 4-fold relative to the as-grown LED. This is due to increase of the light extraction efficiency, which will suppress the total internal reflection effect.

The Raman spectrum is shown in Figure 8. The red shift(E2) in the peak phonon frequency confirms stress relaxation in the PC LED and AAO structure. There was no significant red shift observed for the E2(TO) phonon and the FWHM of the peaks are quite narrow. The absence of disorder-induced Raman bands from the PCs indicates that good crystalline quality was obtained after the process.

The electrical properties of the nano-structure LED is shown in Figure 9. The forward voltage of the AAO LED and PC LED are lower than that of the as-grown LED. The electrical properties of AAO LED were not stable as compared with the PC LED. The underlined mechanism is currently under research.

1-5. Optical simulation properties of the nano-structure LED

The physical model of the PC LED for optical simulation is shown in Figure 10. The LED are composed with p-type GaN/ MQW of InGaN/GaN/ n-type GaN/sapphire. The nano-hole was patterned on the LED. Various structures were designed for the simulation. The simulation parameters include the etching depth, hole size and lattice constant as listed in Figure 11. The enhanced factor was calculated, and the simulation results show that the light extraction efficiency could be increased beyond 40%. The light extraction enhanced factor vs different holes depth is shown in Figure 12. There was an optimized etching depth for the light extraction. The optimium design are; etching depth 0.1um, hole size 0.15um and lattice constant 0.5um.

1-6. Conclusions

In summary, we achieved a nano-structure LED to enhance the light extraction efficiency in III-V nitride LED. The Triangular lattice PC LED with diameter/periodicity of 300/500nm were patterned separately using the AAO template ,E-beam lithography ,and then the ICP etching technique. The PC LED could get low and stable forward voltage as compared to the AAO LED and conventional LED. The optical and electrical properties of the nano-structure LED was demonstrated in this project.

References :

[1] T. N. Oder, J. Shakya, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. 83, 1231(2003).

[2] T. Fujii, Y. Gao, R. Sharma, E.L. Hu, S.P. DenBaars, and S. Nakamura, Appl. Phys. Lett. 84, 855 (2004).

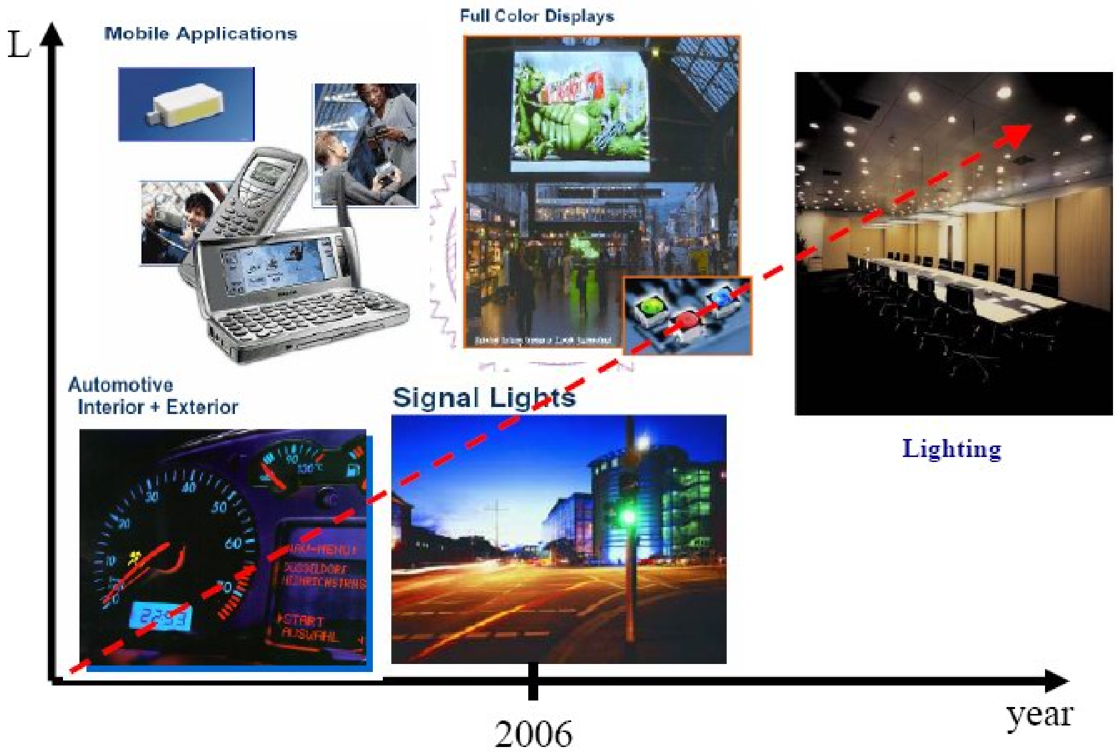

Figure 1. Application field with III-V LED.

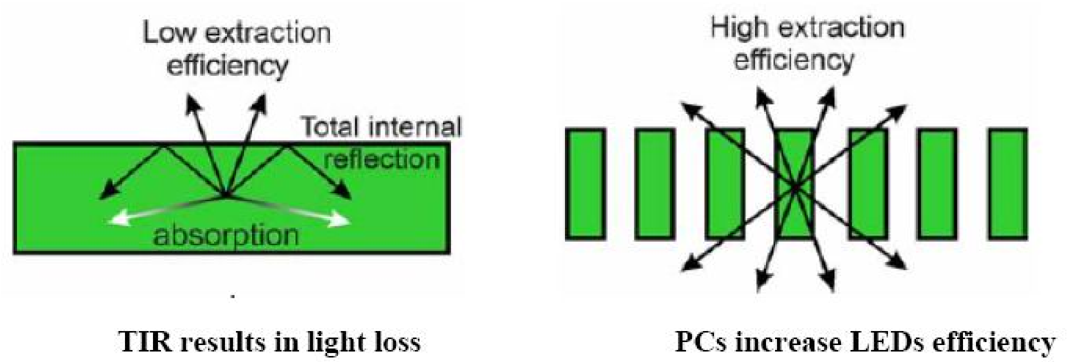

Figure 2. Light extraction efficiency enhanced by photonic crystal structure.

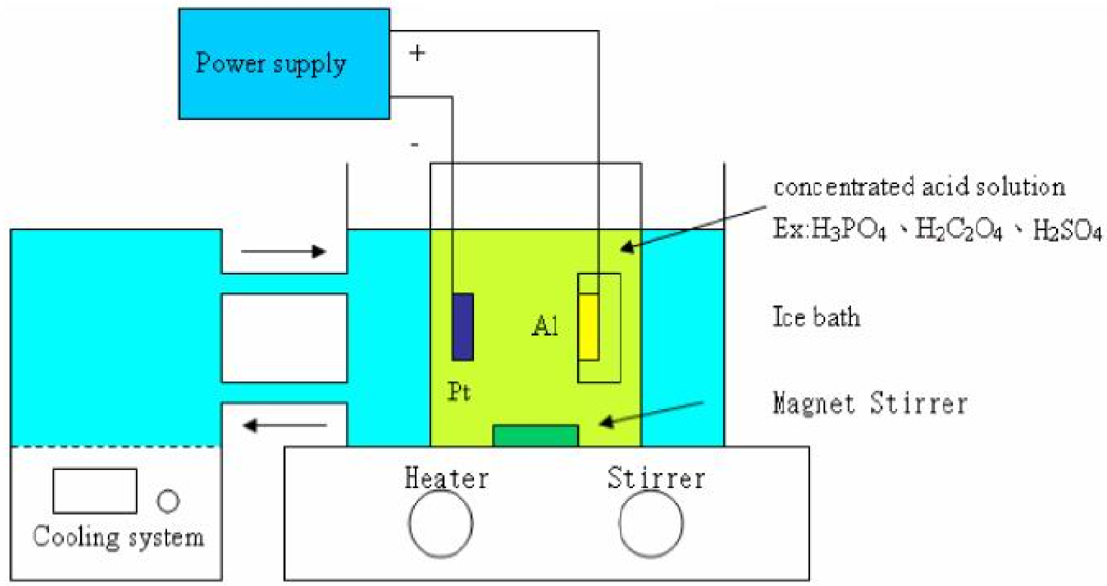

Figure 3. Anodic oxidation system.

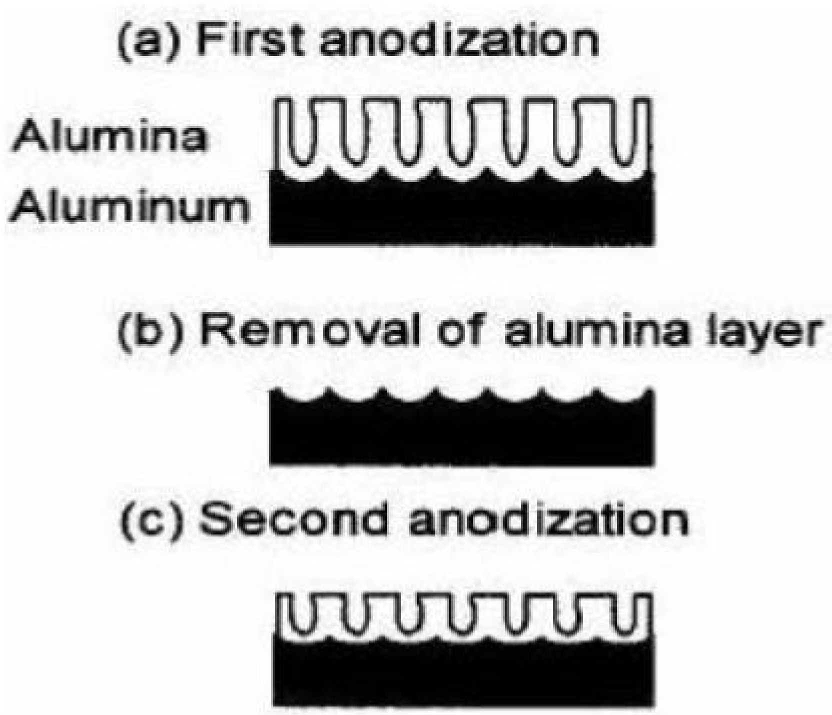

Figure 4. The anodization procedure for AAO layer formation

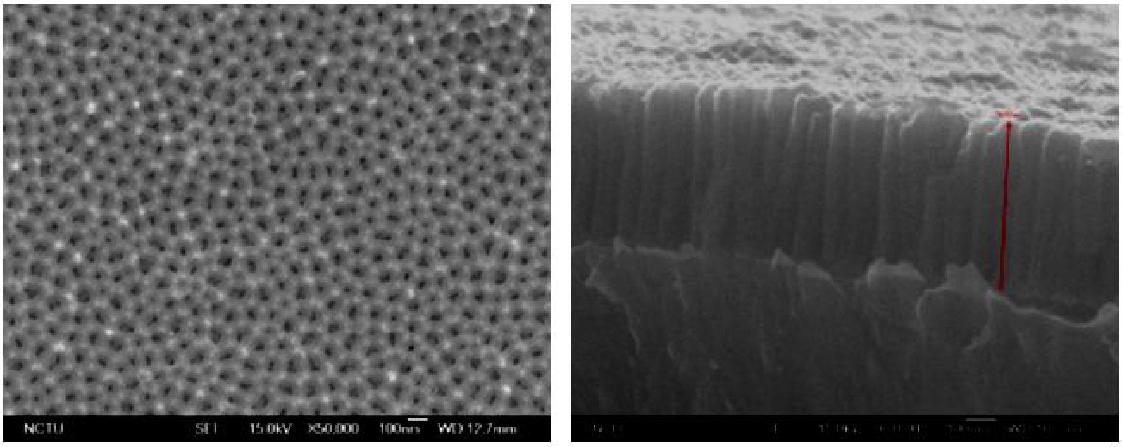

Figure 5. SEM of the AAO layer Left) Top view of the AAO layer Right) Side view of the AAO layer

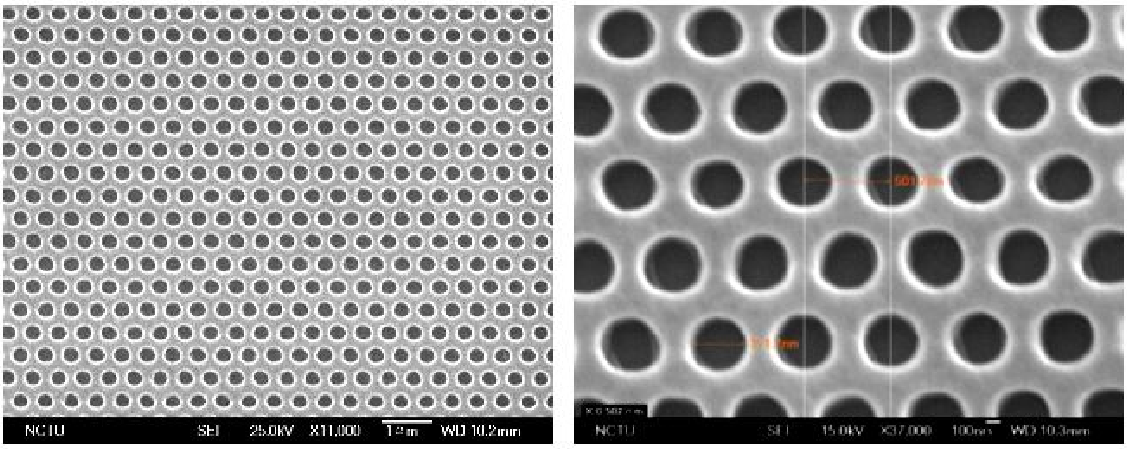

Figure 6. SEM of the 2D PC structure by E-beam lithography method

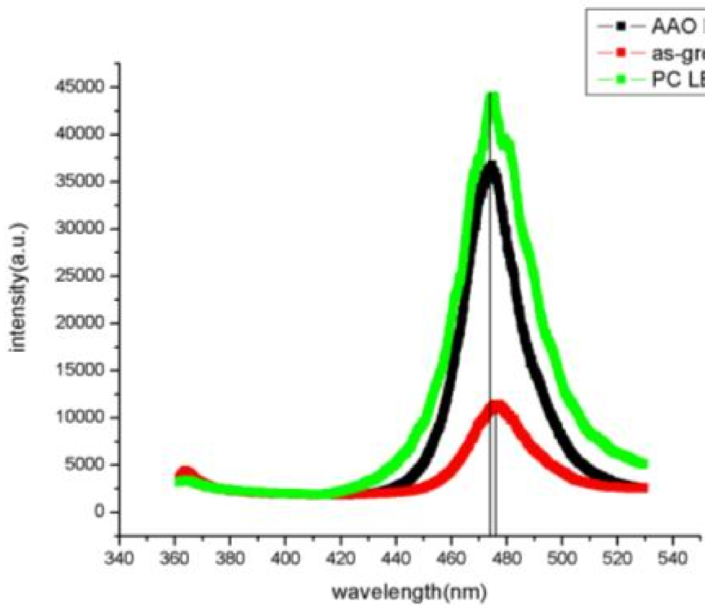

Figure 7. Photo luminescence of AAO and PC LED

GaN bulk	GaN nano-array(AAO)	GaN nano-array(PC)	Symmetry assignment
421	418	418	A1g sapphire
569	567	566	E2(high)
735	733	734	A1 (LO)

Figure 8. The Raman spectrum of the AAO and PC LED

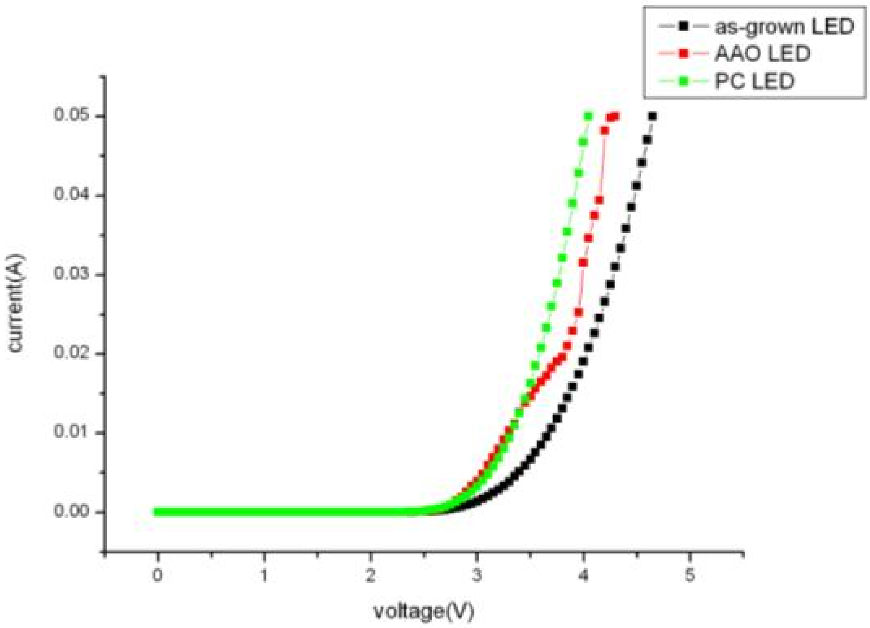

Figure 9. The forward voltage of AAO LED and PC LED

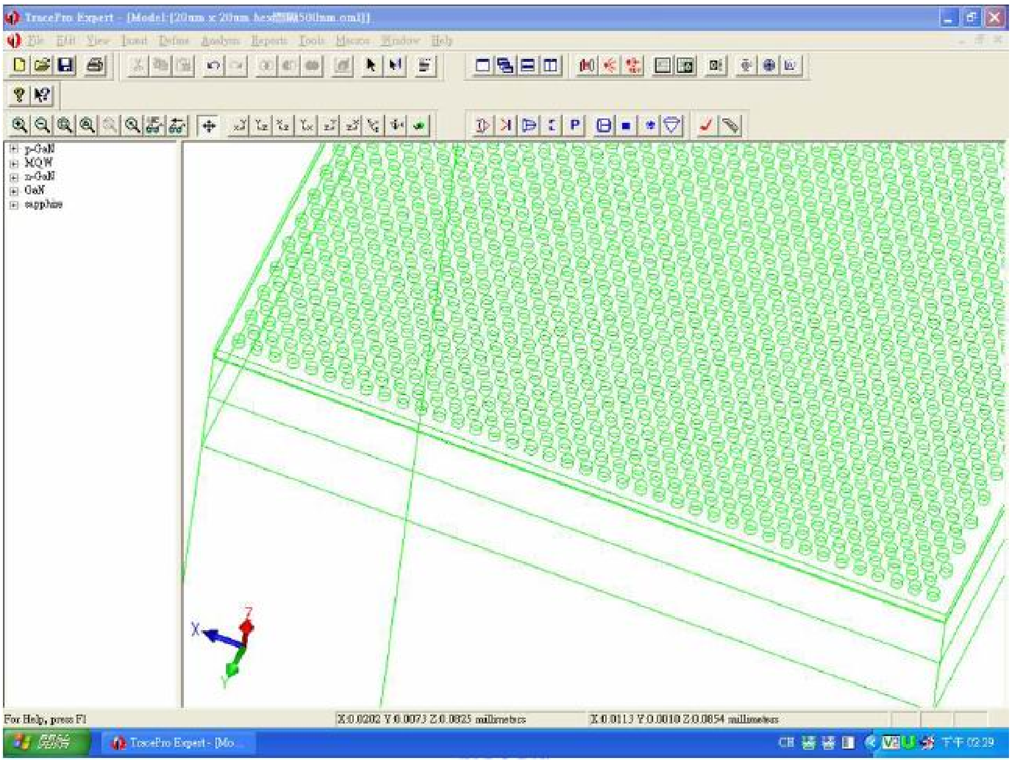
Figure 10. Physical model of the PC LED for optical simulation

hole radius(um)	lattice constant (um)	etching depth (um)	Enhancement factor of
0.075(rec)	0.3	0.1	1.33
0.075(rec)	0.3	0.2	1.24
0.15 (rec)	0.5	0.05	1.37
0.15 (rec)	0.5	0.1	1.40
0.15 (rec)	0.5	0.15	1.36
0.15 (rec)	0.5	0.2	1.33
0.15 (rec)	0.5	0.25	1.31
0.15 (hex)	0.5	0.1	1.41
0.15 (hex)	0.5	0.2	1.38
0.15 (rec)	0.7	0.2	1.31
0.15 (rec)	0.9	0.2	1.28

Figure 11. The structure design and simulation resuls

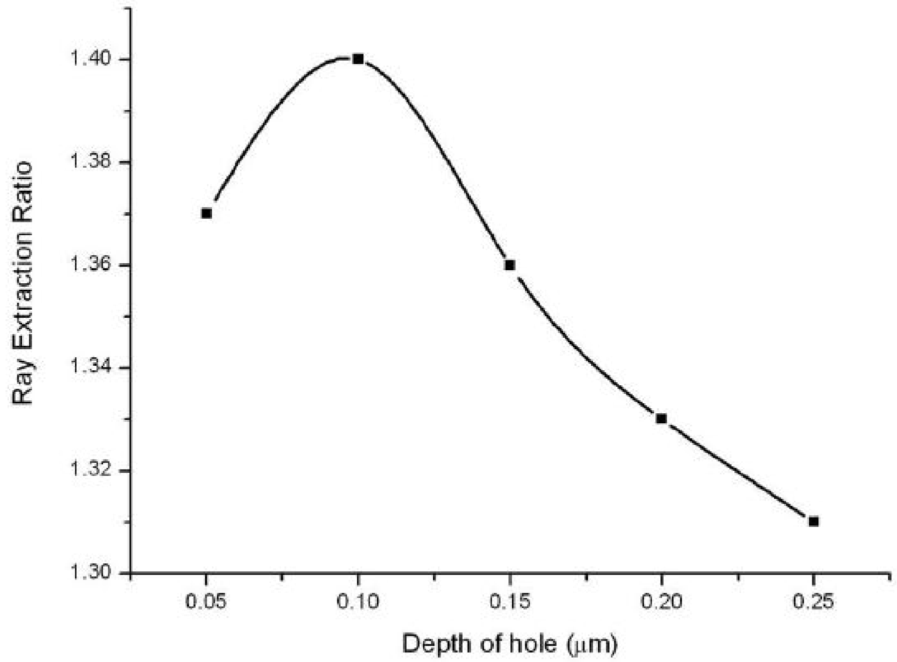

Figure 12. The light extraction enhanced factor vs different holes depth